Uncertainty Analysis for Hot Channel

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Motivation of the work

• **In case of an ATWS event** (inadvertent withdrawal of control assemblies), according to the analysis, **a number of fuel rods are experiencing DNB for a longer time** and must be regarded as failed. Their number must be determined for a further evaluation of the radiological consequences.

• Due to the **small frequency** of the event, the analysis can be of **best estimate type**. (The rod worth and the reactivity coefficients are **exceptions, being conservative** in order to cover the influence of the different reloading schemes of the different cycles.)

•The best estimate approach, namely using the **best estimate power peaking factors** for determination of the failed fuel rods, suspected to be **non-conservative**.

Conservative hot channel calculations:

• **two steps**: global (system) and hot channel calculations

•The **global calculations** are performed in one dimension (symmetric transient) in case of ATWS transient

•The global power history must be multiplied by different **hot channel factors** (kx) taking into account radial peaking factors for each fuel pin (126*349)

•A few number of hot channel calculations to determine the **limiting kx**, leading just to DNB and fuel failure, <u>1.33 conservative DNBR limit</u>

•Knowing the pin power distribution from the core design calculation, **the number of fuel pins with larger peaking factor** can be counted.

How to take into account the uncertainty of the power peaking factors? Using simply the best estimate values? Increasing each fuel pin power with its uncertainty could be probably an extremely conservative approach.

Results of the simulated ATWS transient (conservative and uncertainty analysis)

•tolerance limits method of Wilks (applied also by GRS) was combined with the response surface method

•Only the hot channel parameters were considered as uncertain parameters. Presently, the most important global parameters, namely the rod worth and the reactivity coefficients are conservative.

•input parameters are varied

•distribution-free tolerance limits by Wilks

•one sided tolerance limits

$$\mathrm{P}\left\{\int_{L}^{U} dG(y) > \gamma\right\} = \beta$$

Minimum sample size for some values of γ and β

γ	0.9	0.9	0.9	0.95	0.95	0.95
β	0.9	0.95	0.99	0.9	0.95	0.99
N	**22**	**29**	**44**	**45**	**59**	**90**

•8 steps

•***Step 1***: Identification of the problem.

Inadvertent withdrawal of control assemblies in a VVER-440 type reactor core.

Step 2: Find the sources of the uncertainties and characterize them by corresponding statistical distributions.

Table 2: The sampled input parameters and their distributions, the parameter values used in case of the conservative calculation

Parameter	Type of distribution The uncertainties of the input parameters from earlier studies	Selection (run by run) 59 runs according to Wilks	Selection (run by run and pin by pin, 349*126 pins)	Parameter values in the case of the „conservative" calculation
Uncertainty factor of the pin power (best-estimate values from a 3D distribution of a given reactor state)	Normal sigma=3.907 %		+	kx = 1.496 for Tclad and Tfuel. Core design values for rod failure.
Relative uncertainty of the critical heat flux	Normal sigma= 13.1 % Uncertainty from the measured data (Bezrukov)		+	DNBRlimit = 1.33
Relative uncertainty of the mass flow in the core (Best-estimate value of the mass flow = 8217 kg/s)	Normal sigma= 1.07 %	+		Mass flow = 8217 kg/s

Parameter	Type of distribution The uncertainties of the parameters from earlier studies	Selection (run by run) 59 runs according to Wilks	Selection (run by run and pin by pin, 349*126 pins)	Parameter values in the case of the deterministic calculation
Relative uncertainty of the mass flow in the sub-channel	Normal sigma=2.974 %		+	
Inlet temperature of the coolant	Normal m = 266 ^{o}C sigma=0.667 ^{o}C	+		Tin = 268 ^{o}C
Relative uncertainty of the pin burnup (best-estimate burnup values come from 3D distribution)	Normal sigma= 3.547 %		+	Burnup = 10000 MWd/tU
Initial gap size influencing the gap conductance value	Uniform [0, 1] “0”=80 μm “1”=125 μm		+	“0”=80 μm
Selection of the **power history**	Uniform [0, 1] “0”=conservative curve, “1”=real power history		+	“0”=conser-vative curve

•***Step 3***: Determination of the response surfaces

Mapping module (response surface) determining the best estimate minimum of the critical heat flux ratio (DNBRmin), the max. clad surface temperature and the max. fuel temperature.

In case of DNBRmin, the mapping (input) parameters are the kx (hot channel factor), mass flow, inlet temperature of the coolant, pin average burnup, initial gap size, selection of power history influencing the gap conductance value.

In case of the temperatures, the DNBR limit is additional mapping parameter.

•***Step 4***: Input parameter selection (by using Monte Carlo sampling)

The sampling of the input parameters (mapping parameters) is performed by using the uncertainties given in Table 2.

•***Step 5***: Interpolation in the space dimensioned by the number of the input parameters

Linear interpolation is applied and the dimension is 6 or 7 according to the respective task (response surface for DNBRmin or for the temperatures). This step corresponds to the 'TRABCO runs'.

•***Step 6***: Monte Carlo sampling of DNBR limit

If we want to know that the given fuel pin failed or not failed we have to sample the DNBR limit according to the uncertainty of critical heat flux given in Table 2.

•***Step 7***: Repeating *steps 4, 5 and 6* for each Wilks's run

We want to get one-sided tolerance limit with a probability content (*g*) of 95 % and a confidence level (*b*) of 95 %, which is needed to perform 59 Wilks's run according to Table 2.

•***Step 8***: Statistical evaluation according to the Wilks theory

We determine the conservative one-sided limit for the selected output parameters according to γ = 0.95 and β = 0.95. The sensitivity investigations are performed by using correlation coefficients of Pearson between the input and the selected output parameters. The results are shown by figures and interpreted below.

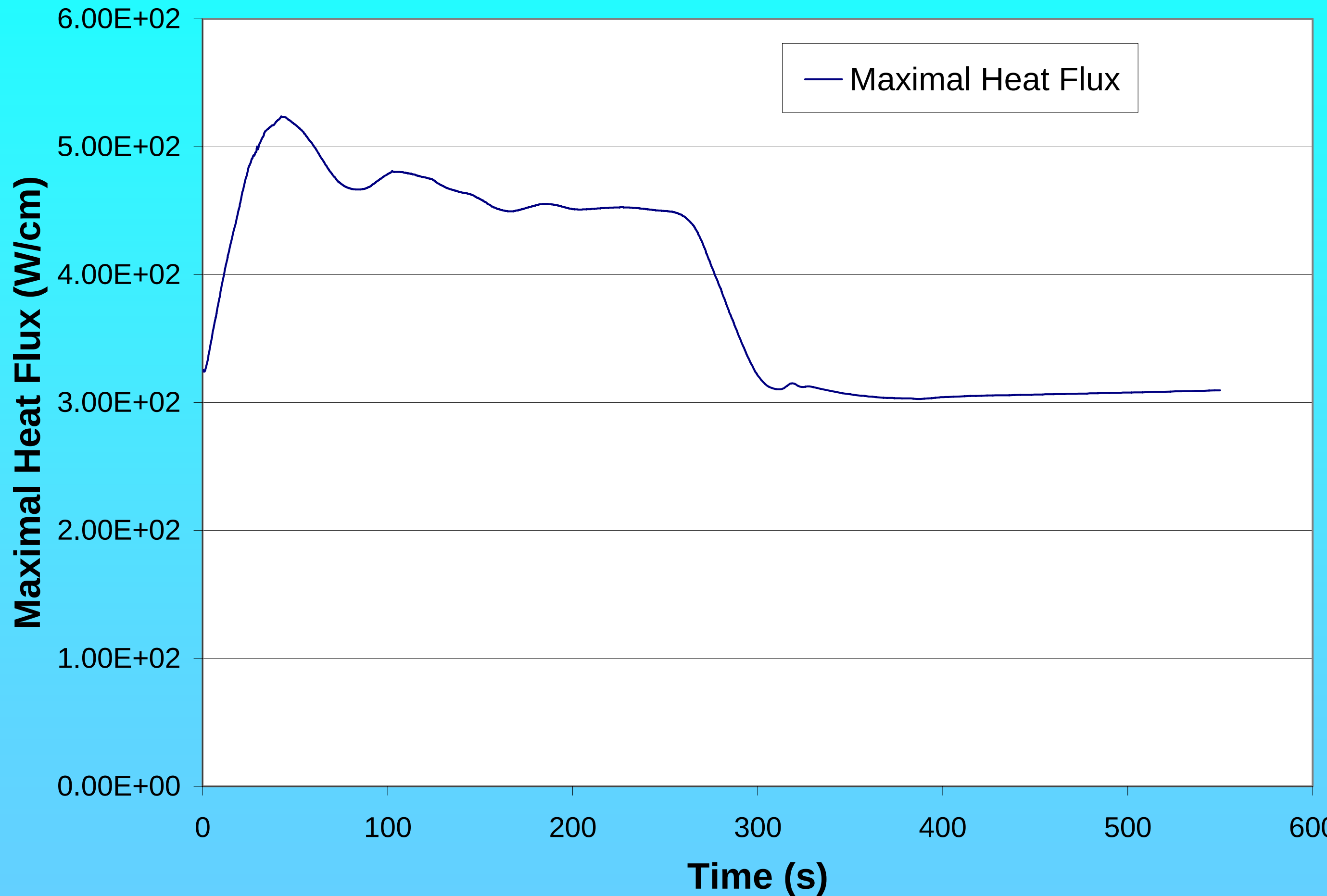


Figure 1: Maximum heat flux in the hot channel, in case of conservative calculation

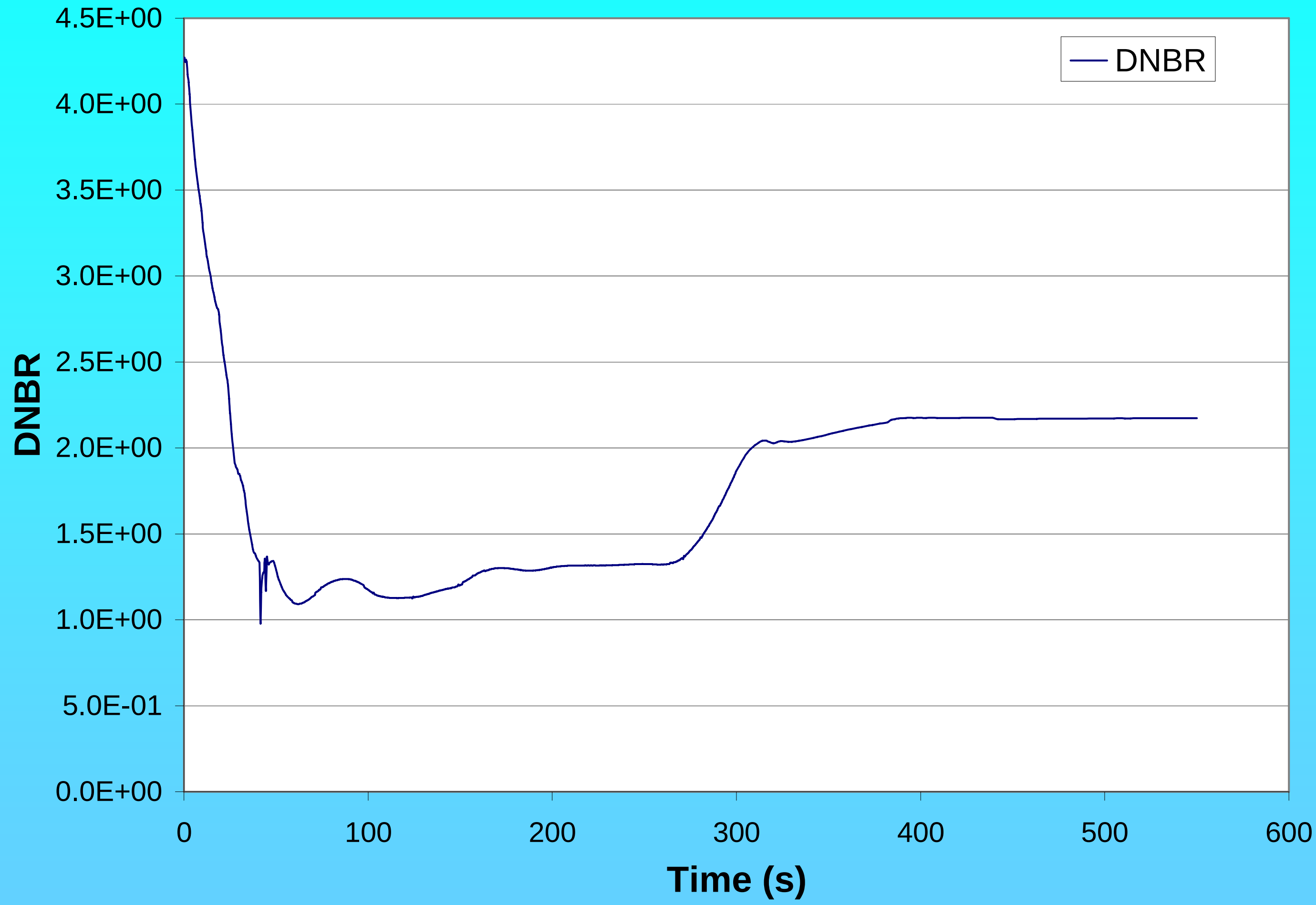


Figure 2: Minimum critical heat flux ratio (DNBR) in the hot channel, in case of conservative calculation

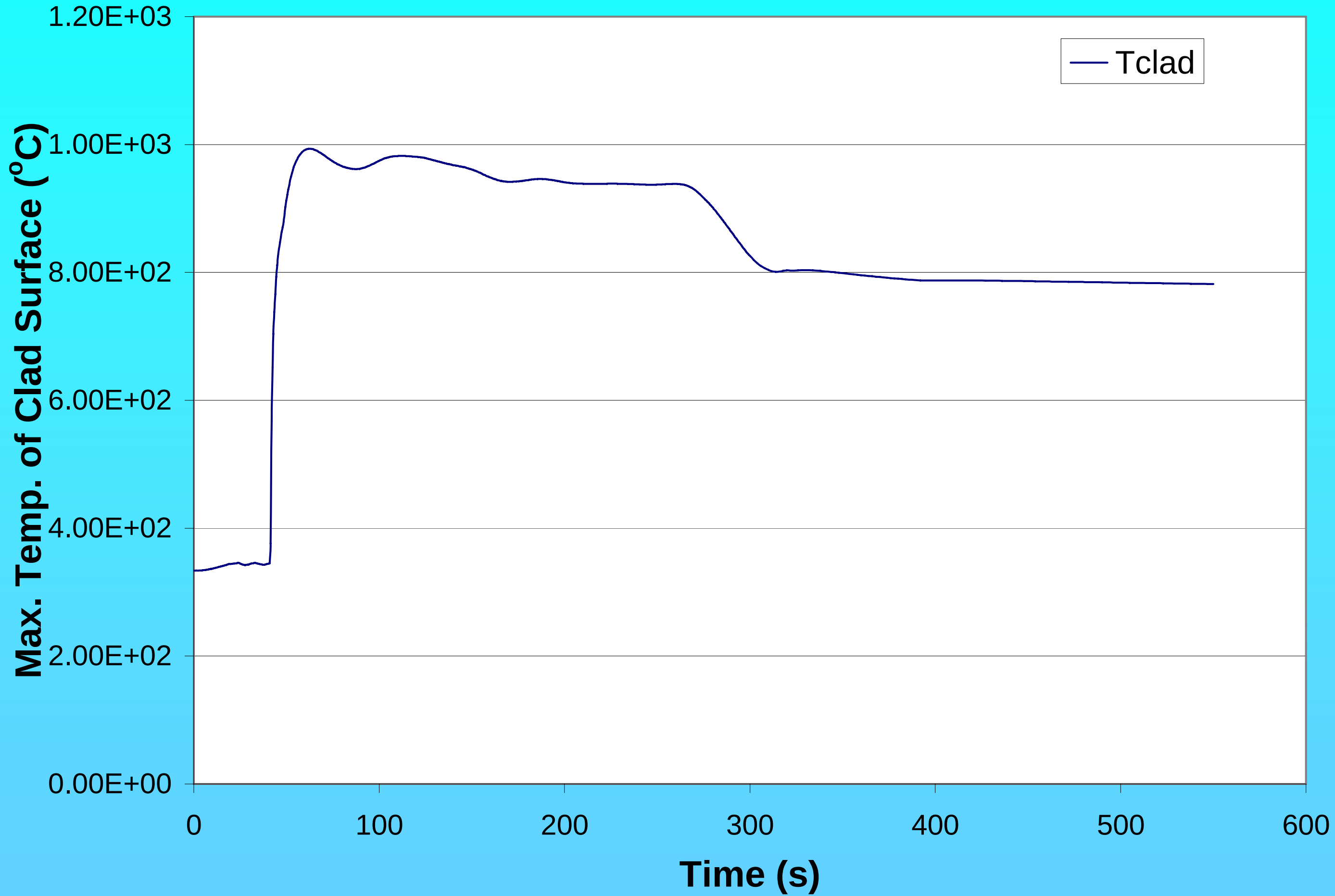


Figure 3: Max. clad surface temperature in the hot channel, in case of conservative calculation

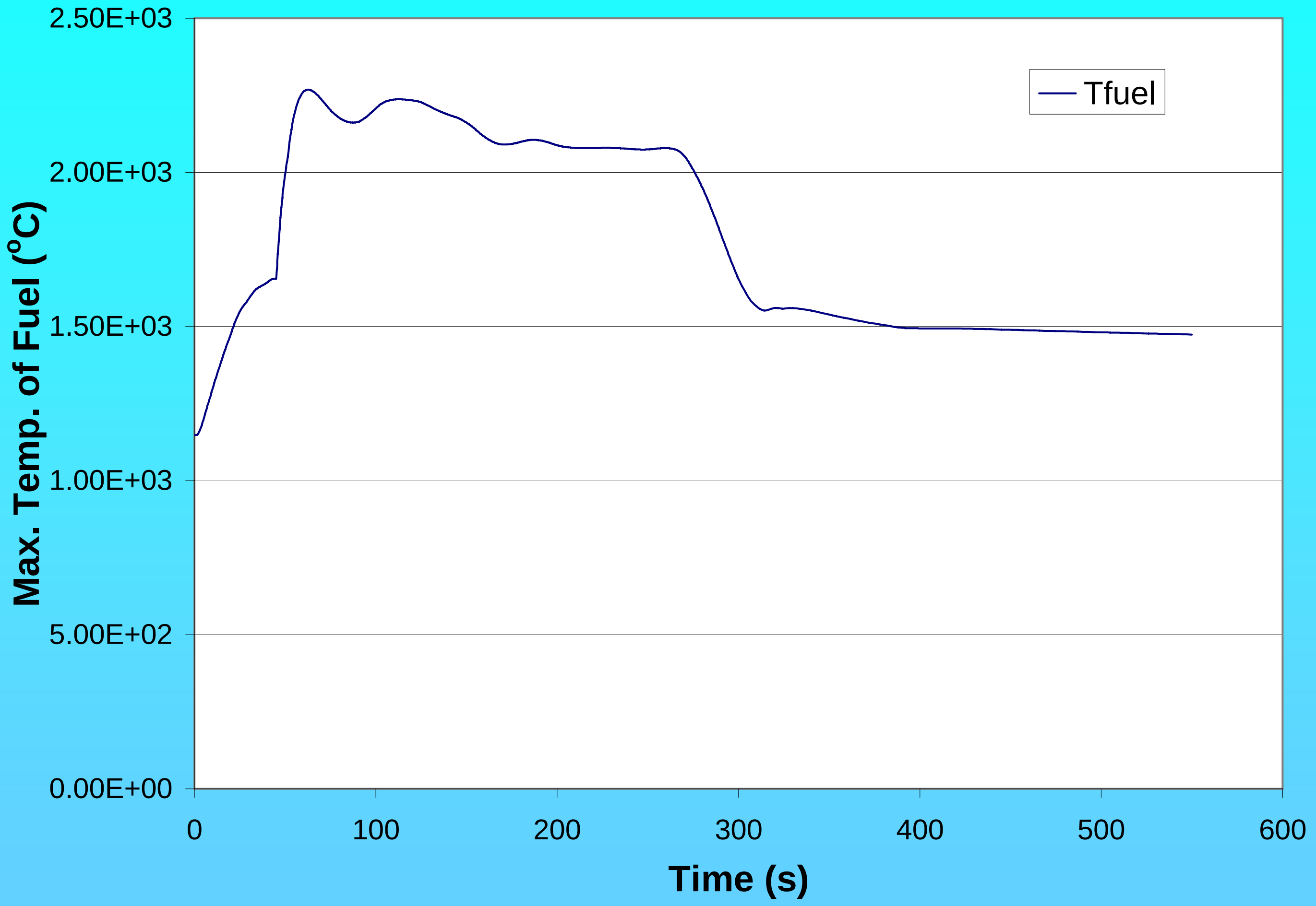
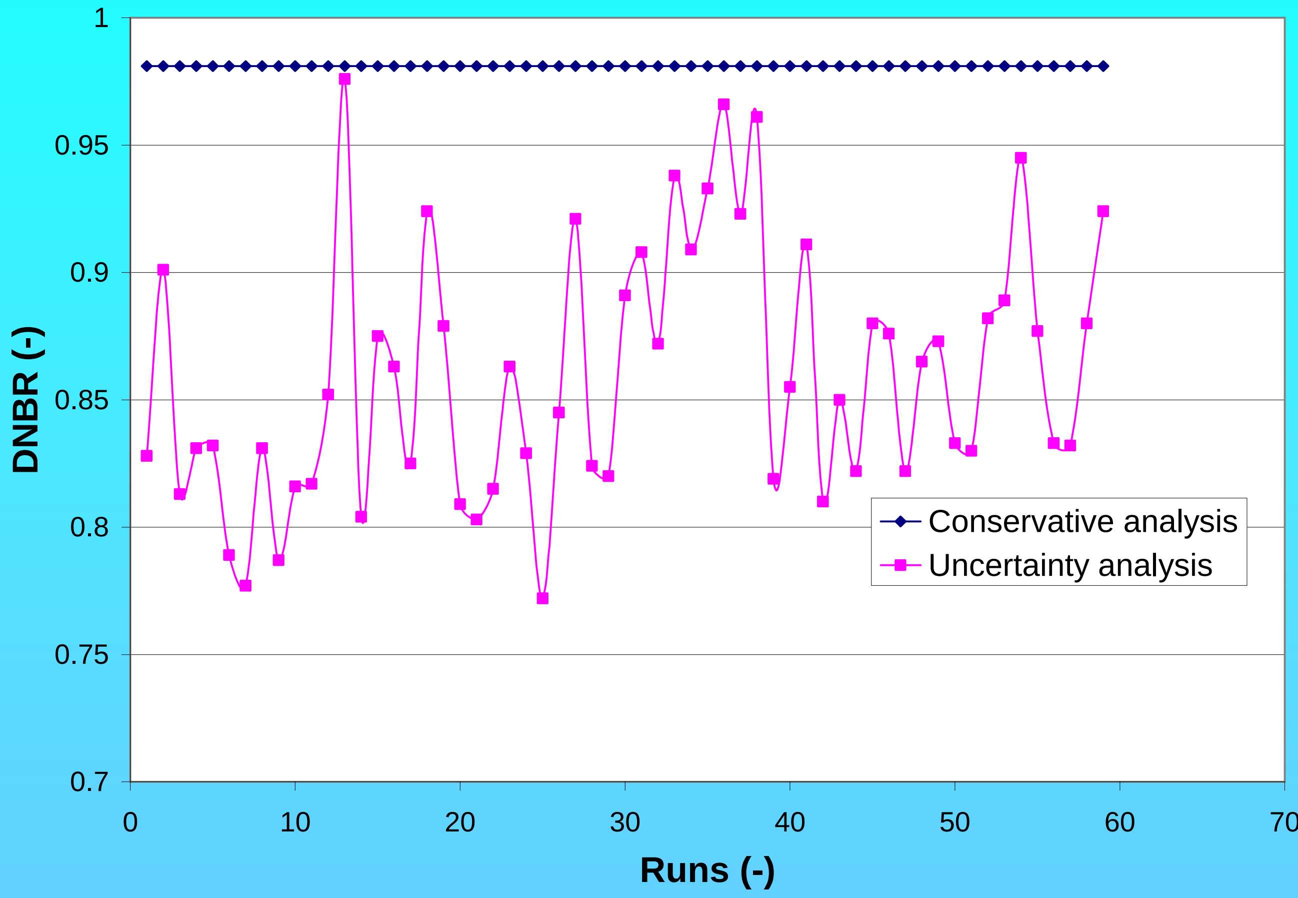


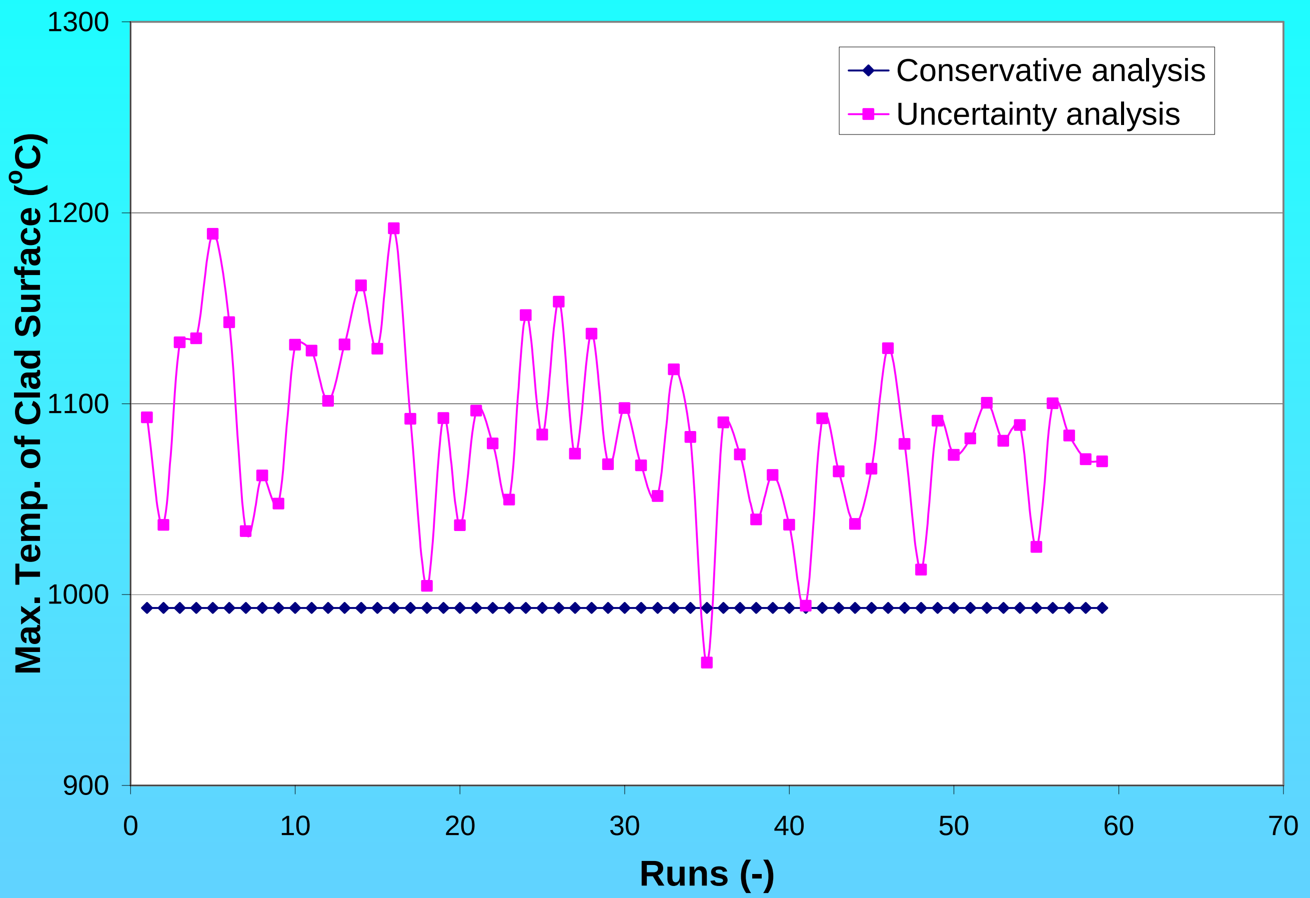
Figure 4: Max. fuel temperature in the hot channel, in case of conservative calculation



DNBR = 0.981 (C. A.)

Lower limit=0.772 (U. A.)

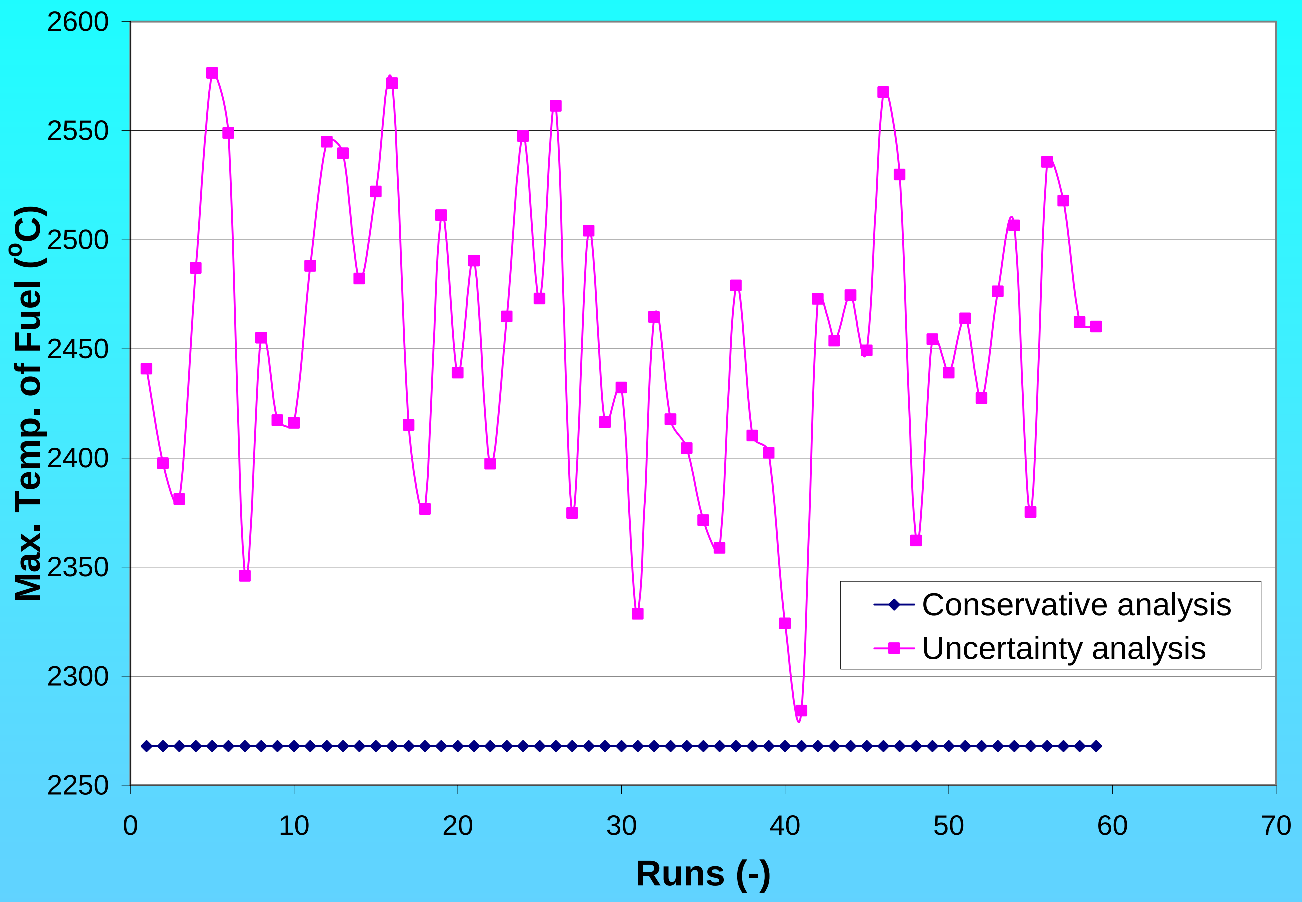
Figure 5: Minimum critical heat flux ratio (DNBR) in the hot channel, in cases of conservative and uncertainty analysis



Tclad = 993 °C (C. A.)

Upper limit= 1192 °C (U. A.)

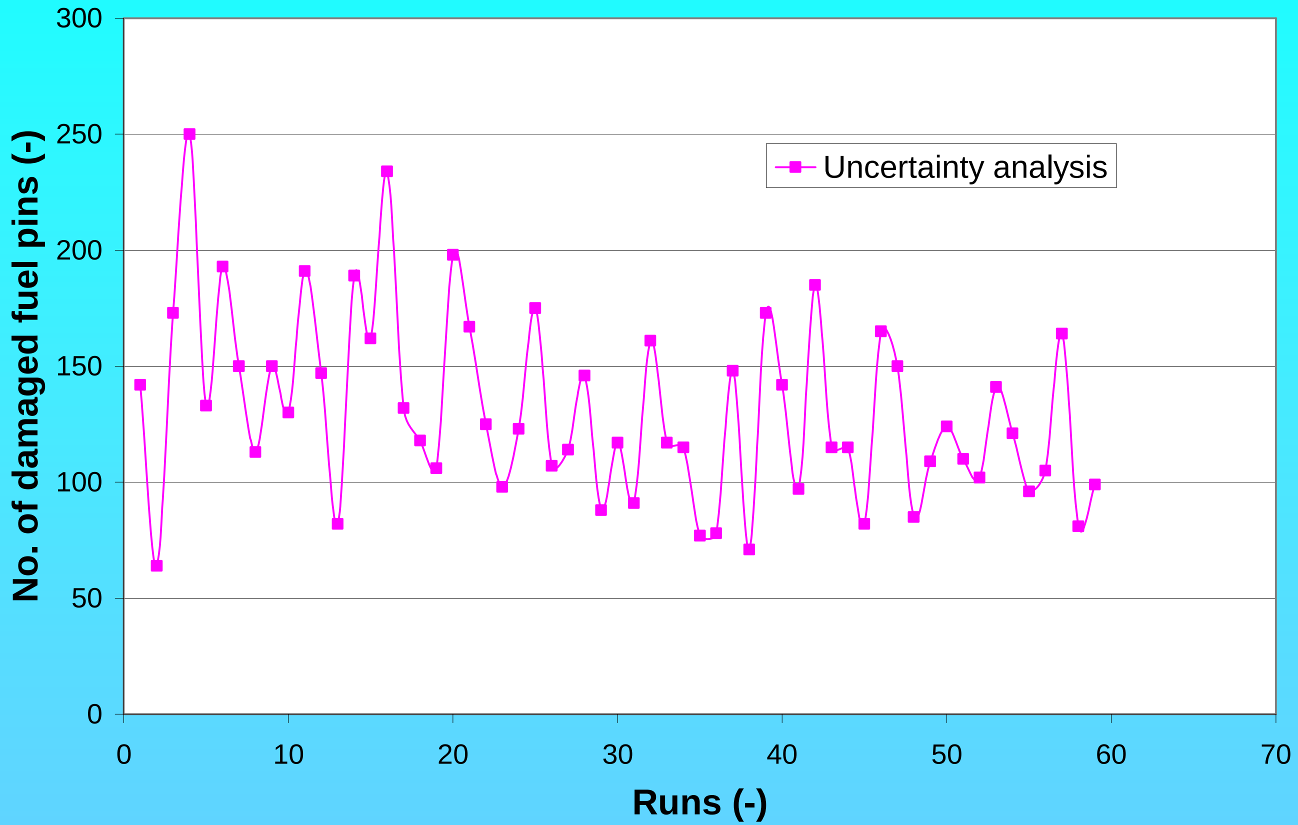
Figure 6: Maximum clad surface temperature in the hot channel, in cases of conservative and uncertainty analysis



Tfuel = 2268 °C (C. A.)

Upper limit= 2577 °C (U. A.)

Figure 7: Maximum fuel centerline temperature in cases of conservative and uncertainty analysis



Upper limit = 250 (U. A.)

Figure 8: No. of failed fuel pins, in case of uncertainty analysis

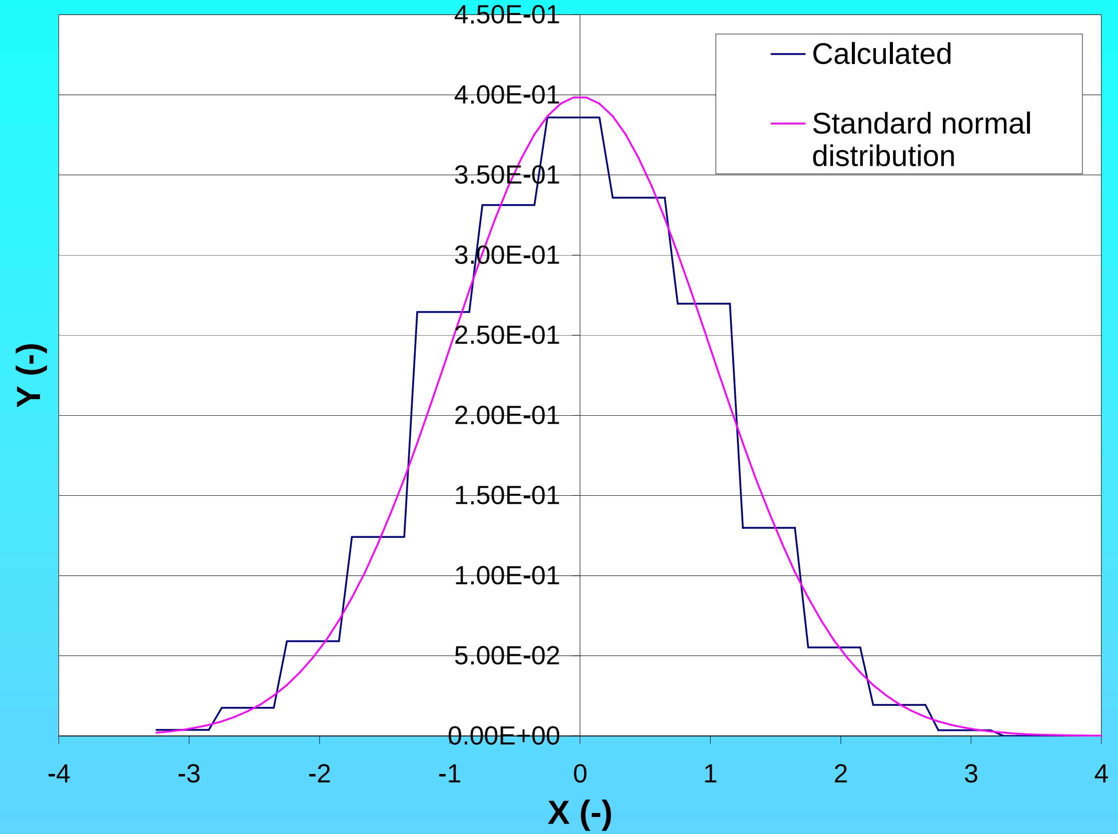


Figure 9: Normalized histogram of failed fuel pins (m=989.8, sigma=61.3) from large number of „conservative analysis" by varying the hot channel factor only according to its uncertainty. The „conservative" number of damaged fuel pins = 989.8+2*61.3=1113. Concerning the hot channel factor uncertainty, 1/0.95 result in the Wilks terminology)

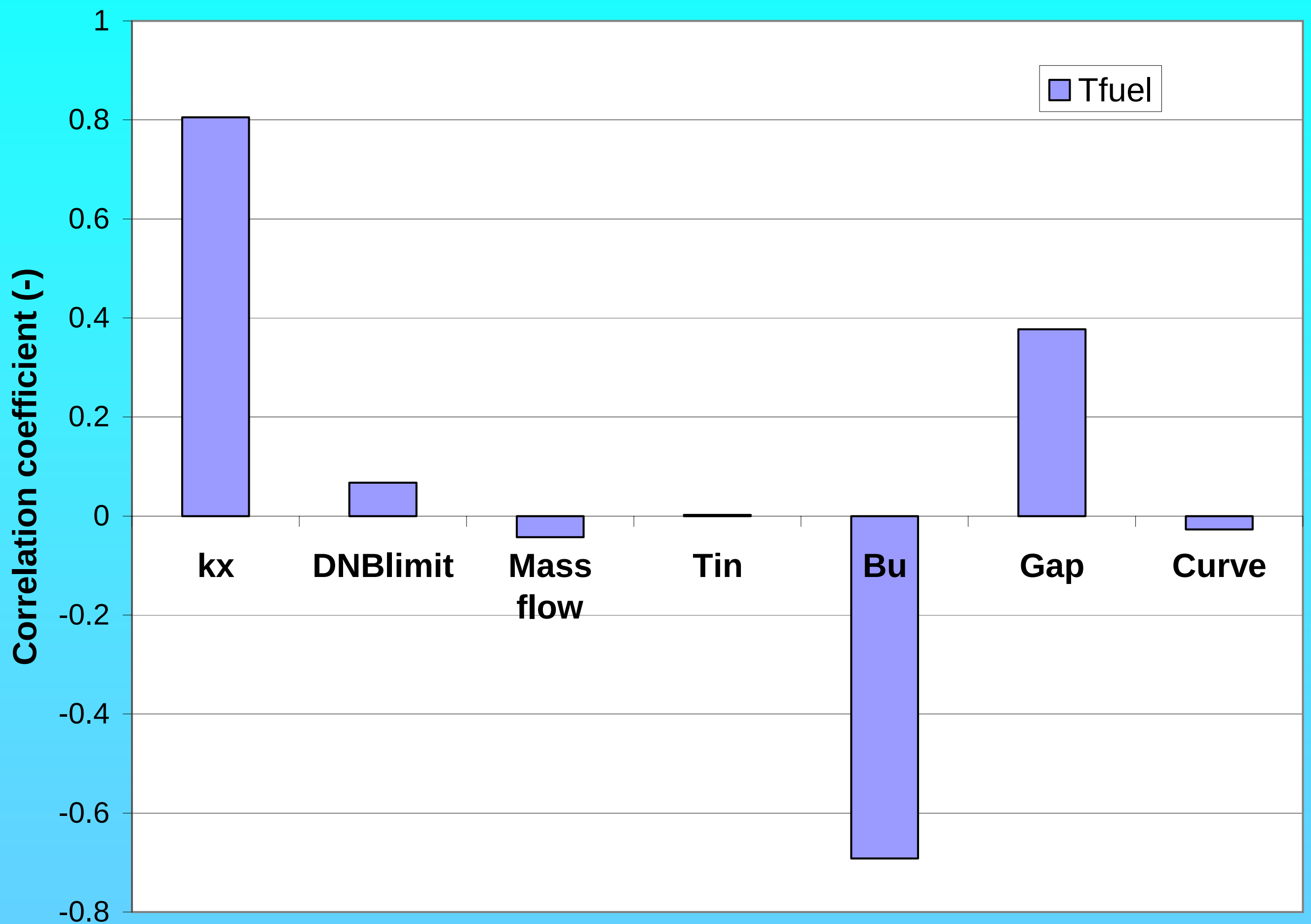


Figure 10: Correlation coefficients between the max fuel temperature and the input parameters

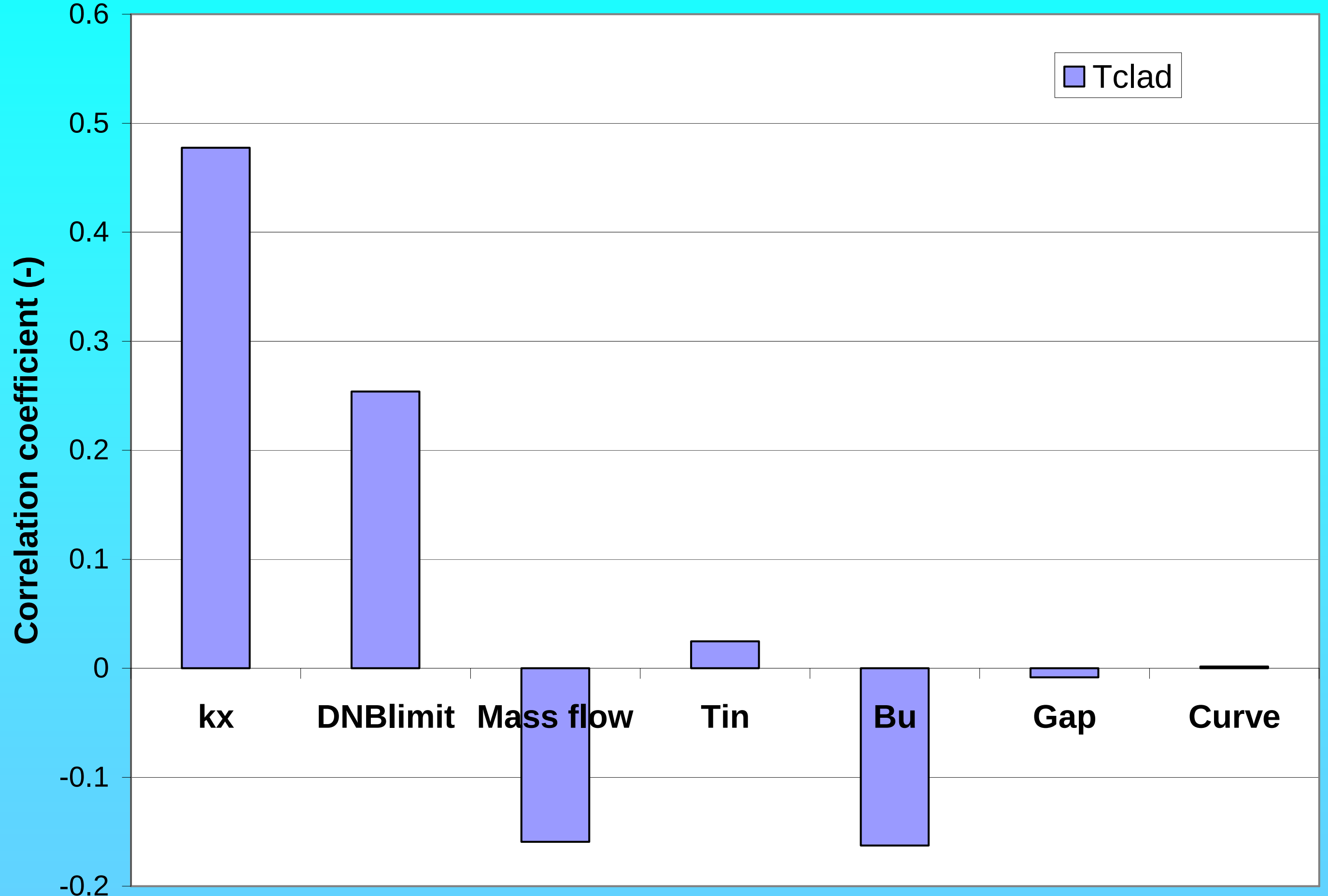


Figure 11: Correlation coefficients between the max. clad surface temperature and the input parameters

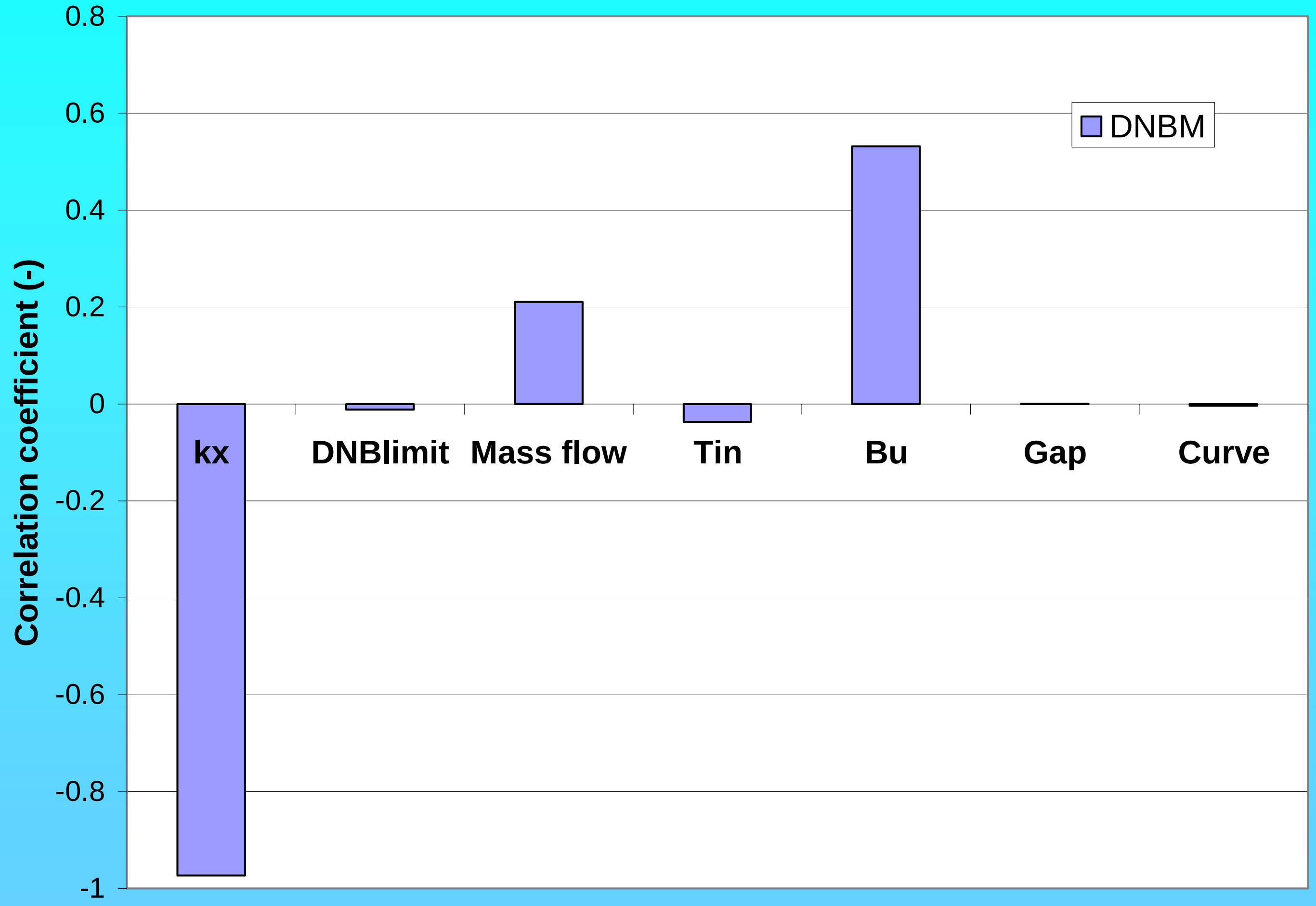


Figure 12: Correlation coefficients between the DNBM and the input parameters

Number of failed fuel rod from different approaches

„**Conservative” analysis**, each pin power is increased by **3*sigma** uncertainty (1.33 conservative DNBR limit): **8276**

„ **Conservative” analysis**, each pin power is increased by **2*sigma** uncertainty (1.33 conservative DNBR limit): **5105**

„ **Conservative analysis**”, **best estimate** pin power distribution (1.33 conservative DNB limit): **527**

Which is slightly non-conservative in comparison to the number below.

„ **Conservative analysis**” but pin power is **sampled** according to its uncertainty (1.33 conservative DNBR limit) (1.0/0.95 value): **1113**

Full hot channel uncertainty analysis, 0.95/0.95 value (including DNB limit): **250**

Summary

- One sided tolerance limits method of Wilks (applied also by GRS) was combined with the response surface method in order to evaluate to number of failed fuel rods (and other parameters) in the hot channel calculations.
- The elaborated modules were applied in case of an ATWS event (inadvertent withdrawal of control assemblies).
- The analysis should be complemented with the uncertainties from the global calculation.
- The estimated number of fuel rods depends to great extent on the applied uncertainty approach of the hot channel calculation.
- Simple use of the best estimate power distribution is slightly non-conservative concerning the failed fuel rods.
- Full hot channel uncertainty analysis leads to minimum number of failed fuel rods in 0.95/0.95 sense.